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Cryocooler conduction-cooled SRF cavities for compact particle accelerators

Ram C. Dhuley on behalf of Fermilab's conduction-cooled SRF project team

Accelerator Physics and Technology Seminar, Fermilab

02 June 2020

IARC at Fermilab

Mission: Partner with industry to exploit technology developed in the pursuit of science to create the next generation of industrial accelerators, products, and new applications.

Partners

- MWRD of Greater Chicago
- US Army Corps of Engineers (ERDC)
- Northern Illinois University
- Euclid Beamlabs
- General Atomics

Facilities

- Several 4 K cryocoolers, cryogenic test stands, LHe refrigerator
- LLRF system, solid state RF power source (20 kW)
- 9 MeV, 1 kW electron accelerator (A2D2)

Contact

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https://iarc.fnal.gov/

Outline

Motivation: SRF accelerators for industrial applications

- Potential applications and the scope of SRF accelerators
- Cryocooler conduction-cooled SRF cavities
  - Development at Fermilab
  - First results
  - Ongoing R&D
- Fermilab's conduction-cooled SRF accelerator program
- New R&D being facilitated by conduction-cooled SRF
- Summary and outlook

Industrial applications and the scope of SRF accelerators

Electron beam radiation processing applications

- Water/sludge/medical waste decontamination
- Flue gas cleanup
- Medical device sterilization
- Strengthening of asphalt pavements

Radiation processing requires:

- Beam energy: 0.5-10 MeV
- Beam power: >>100 kW

Industrial settings demand:

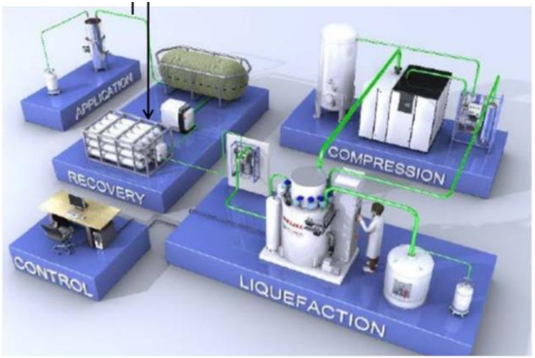
- Low capital, operating expense
- Robust, reliable, turnkey operation

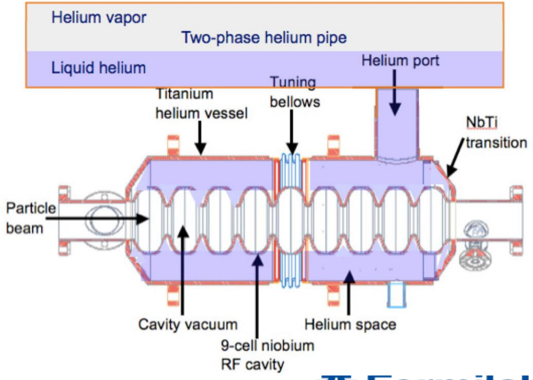
http://accelconf.web.cern.ch/AccelConf/napac2016/talks/thb3io02_talk.pdf

A meter-long SRF linac (niobium or Nb_3Sn cavities) operating at 10 MV/m can provide the required energy

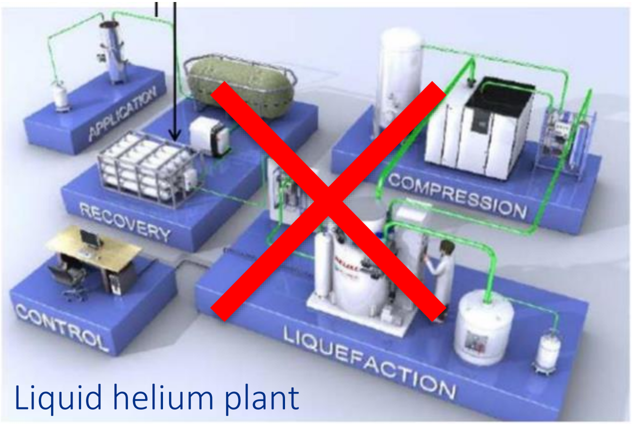
Small SRF surface resistance enables continuous wave (cw) operation that can lead to high beam power

At present, SRF accelerators are designed to operate with complex liquid helium cryogenic systems!





Simplifying SRF cryogenics for industrial settings

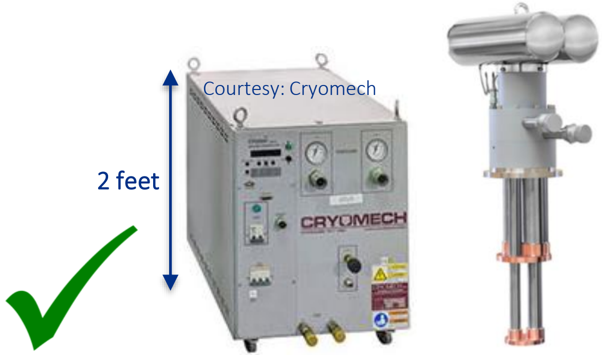


Nb_3Sn cavity dissipates ~6-8 W @ ~4.5 K

(1 m x 10 MV/m cw; 650 MHz/1.3 GHz)

Use commercial, off-the-shelf 4 K cryocoolers

(helium plant not required)



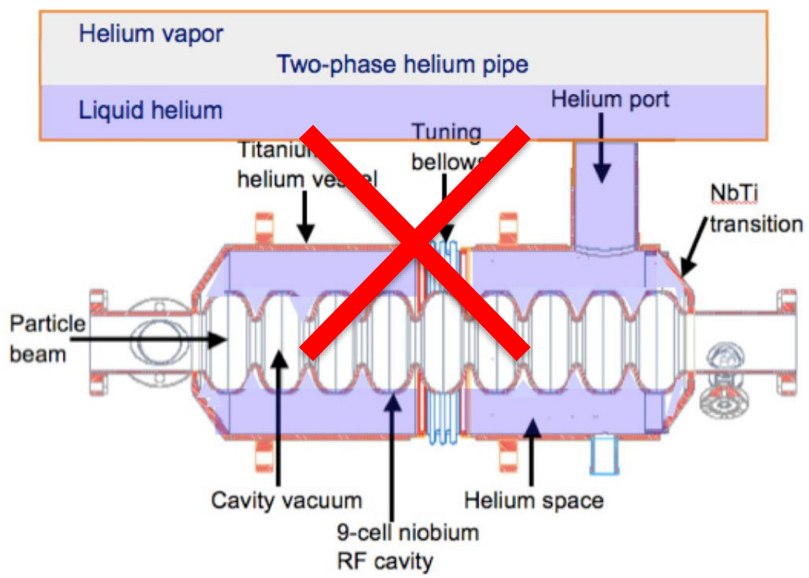
Cryocoolers offer

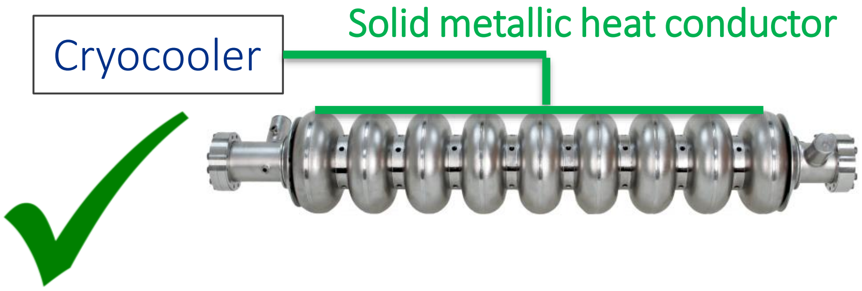
- Closed cycle cooling at ~45 K and ~4 K
- Compact, small footprint
- Reliability (MTBM > 2 years non-stop operation)
- Turnkey operation (no trained operator needed, turn ON/OFF with push of a button)

Simplifying SRF cryogenics for industrial settings

Remove cavity dissipation *via* thermal conduction (conduction cooling)

(conventional liquid helium bath not required)





Absence of cryogenic liquids

- Compact, simplified construction
- No pressure vessel safety concerns
- Facilitates deployment in remote locations

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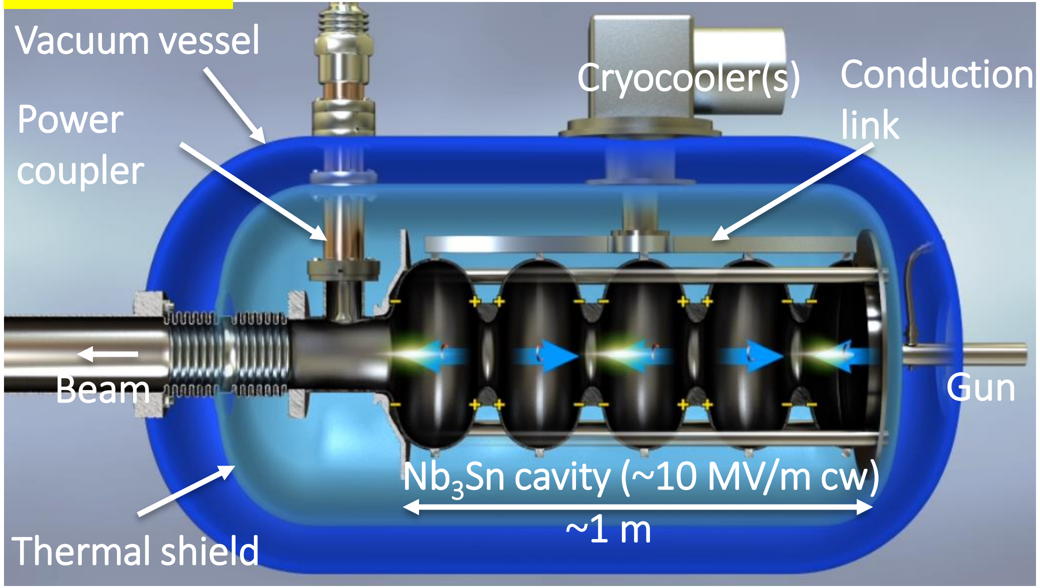
Concept of a cryocooler conduction-cooled SRF accelerator

R.D. Kephart, ***SRF2015***, 2015. https://accelconf.web.cern.ch/srf2015/papers/frba03.pdf
Patents: **US10390419B2**, **US10070509B2**, **US9642239B2**

Illustration



All of the cryogenics integrated into the module

- Cryocooler 4 K stage cools the SRF cavity
- Cryocooler 45 K stage cools thermal shield/intercept
- Enclosed in a simple vacuum vessel

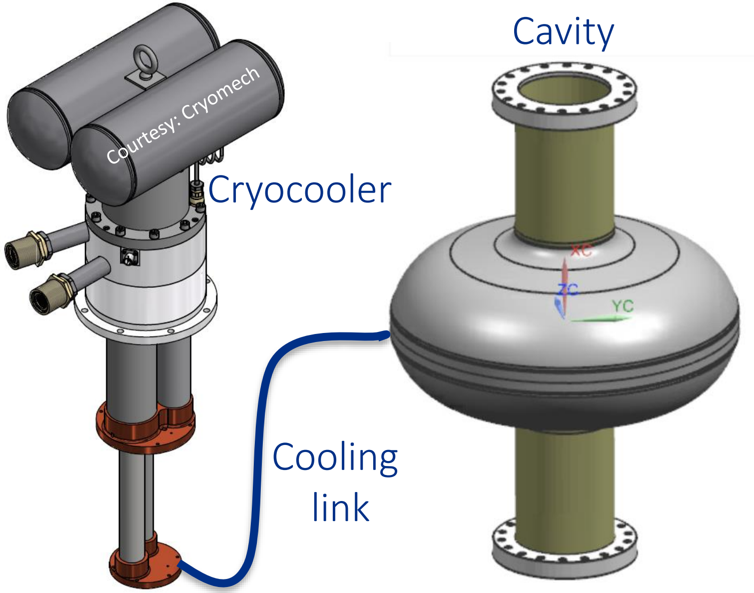
Conduction-cooled SRF cavity development at Fermilab

- Supported by Fermilab Laboratory Directed Research and Development (LDRD) 2017-2019

Goal: To demonstrate 10 MV/m cw on an SRF cavity with cryocooler conduction-cooling

Our choices:

- Single cell 650 MHz, Nb_3Sn coated niobium cavity
- Cryomech PT420 cryocooler (2 W @ 4.2 K with 55 W @ 45 K)
- High purity aluminum for the conduction cooling link



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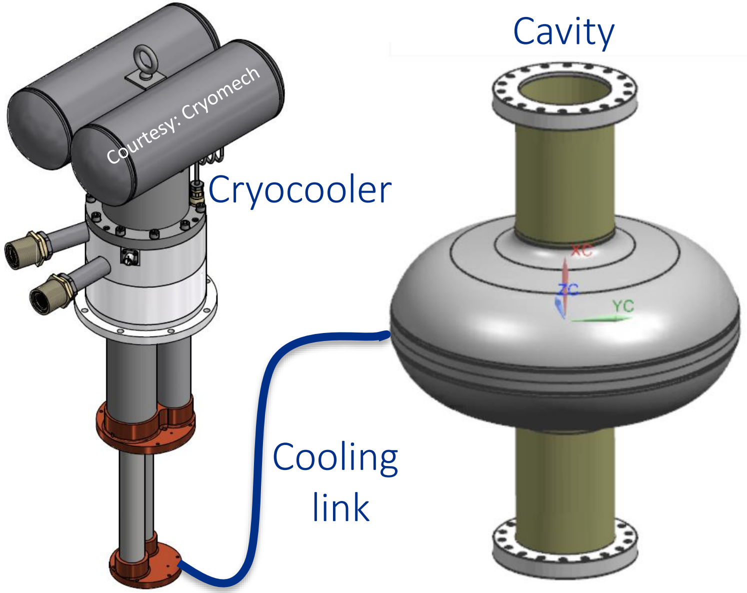
Design for conduction cooling

- Cavity preparation for attaching the cooling link
- Characterization of thermal resistance
  - thermal contact resistance of aluminum-niobium at the link-cavity joint
  - bulk thermal resistivity of the high purity aluminum
  - aluminum-aluminum contact resistance
- Mechanical design
- Verification *via* FEA simulations



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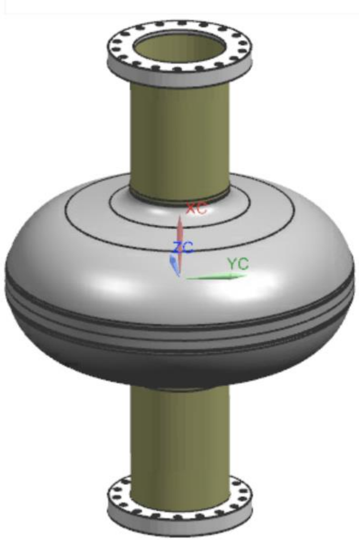
Cavity preparation for thermal link attachment

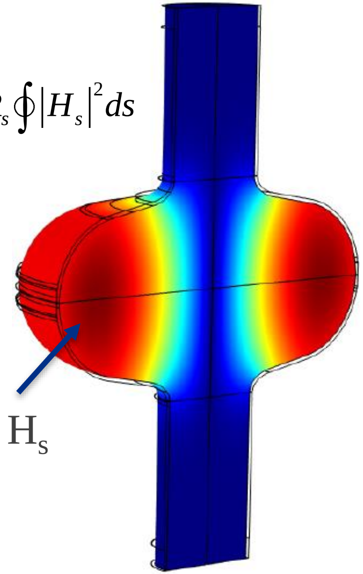
Need a thermal link attachment point on the niobium cavity shell



⇨

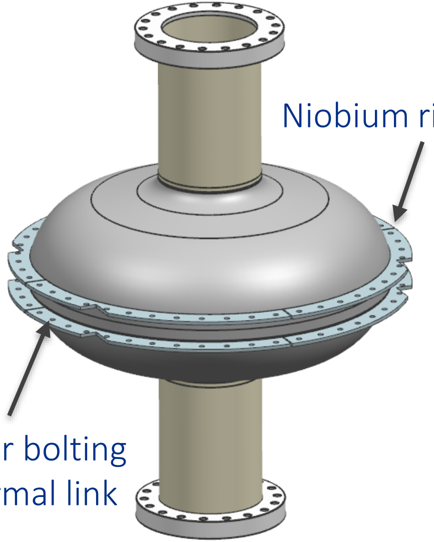
Dissipation is prominent near the equator

$$P_{diss} = \frac{1}{2} R_s \oint |H_s|^2 ds$$



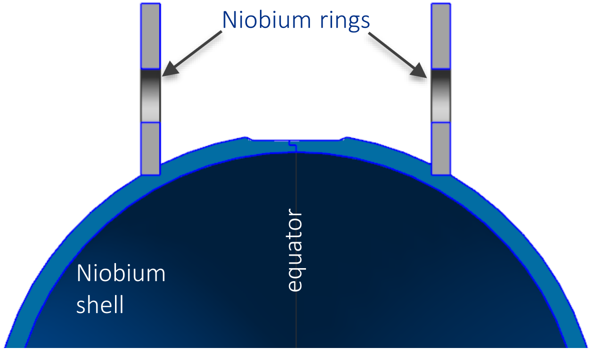
⇨

Solution: E-beam weld niobium cooling rings near the equator



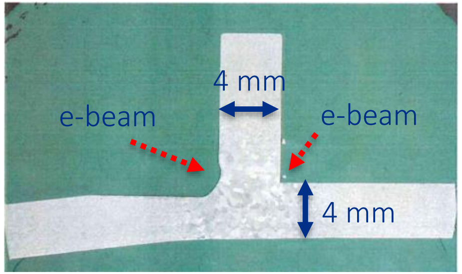
Cavity preparation for thermal link attachment

Joint design for e-beam welding

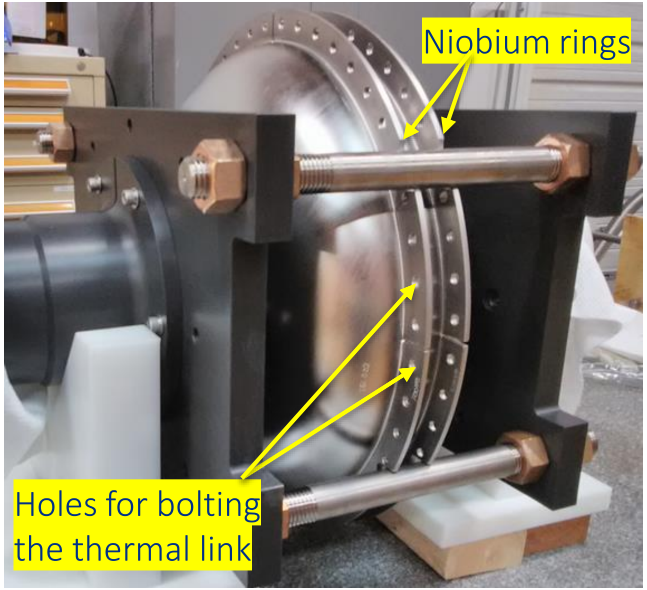


Weld development

- Full penetration for thermal conductivity
- Avoid weld beads on the RF surface



Single cell cavity ready for conduction cooling



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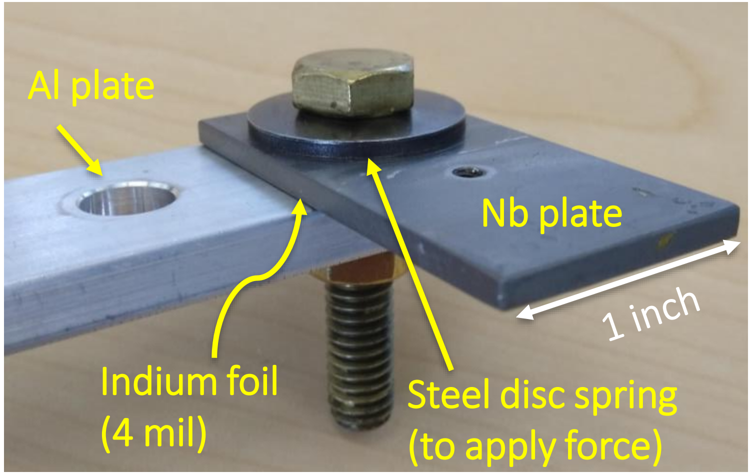
Characterization of thermal resistance

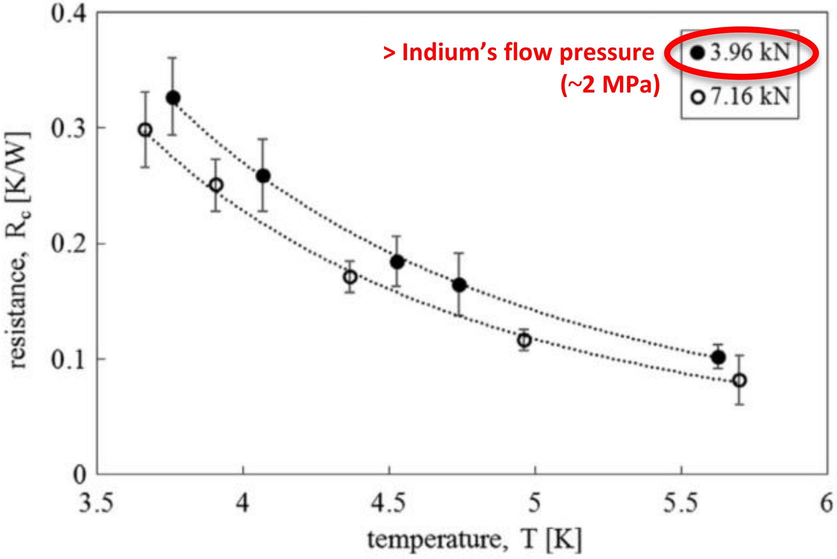
1. Cavity-link (niobium-aluminum) bolted thermal contacts

Test joint details



R.C. Dhuley, M.I. Geelhoed, J.C.T. Thangaraj, ***Cryogenics***, 2018.
https://doi.org/10.1016/j.cryogenics.2018.06.003

Joint thermal resistance



Selected design: 4 mil indium, ~4 kN force

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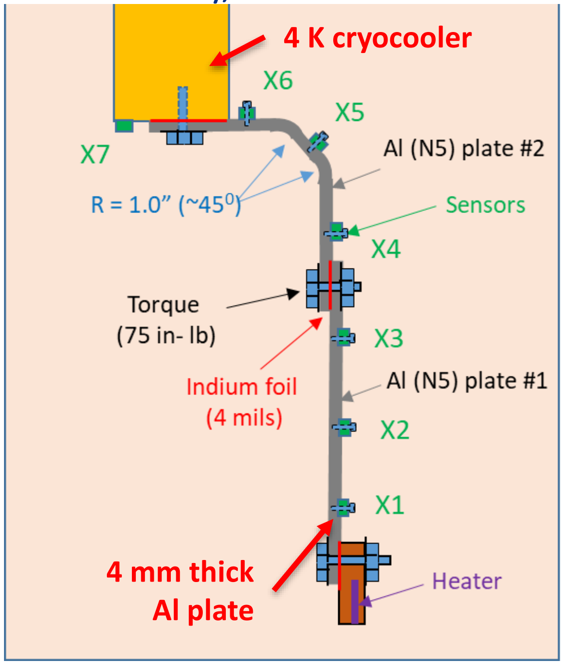
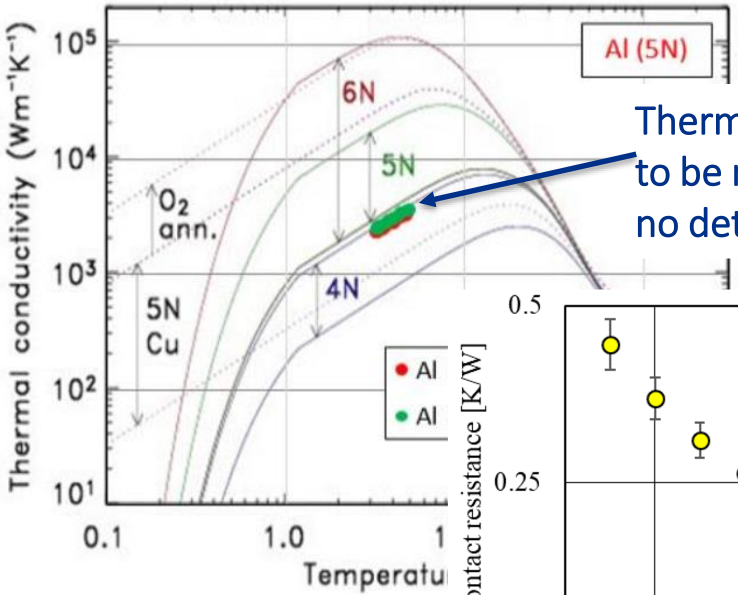
Characterization of thermal resistance

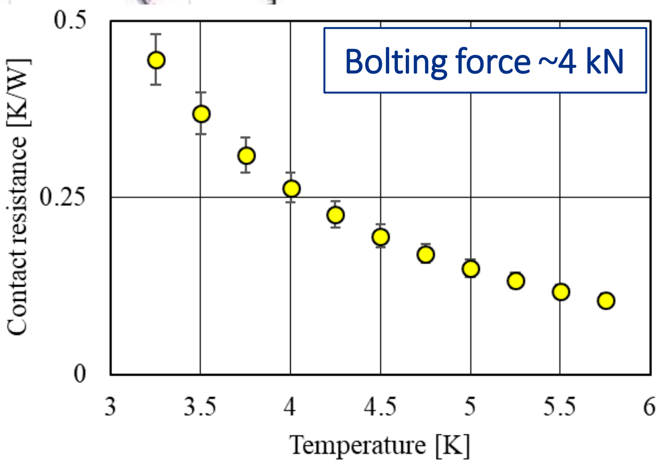
2. Thermal characterization of high purity aluminum

Setup for measuring 4 K thermal conductivity, contact resistance





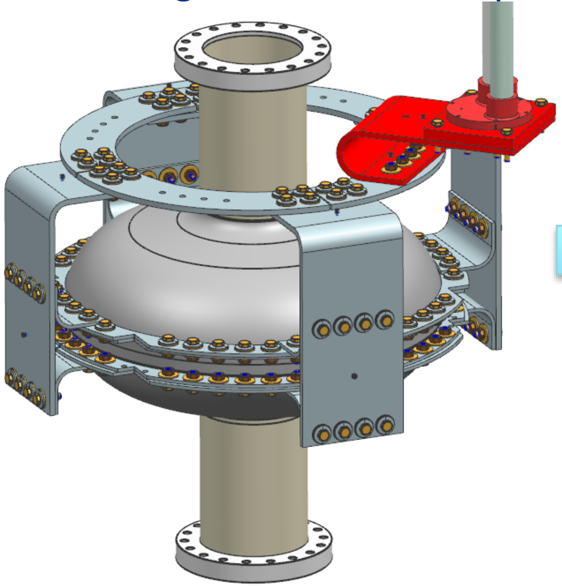
Thermal conductivity found to be near the lower band of 5N, no deterioration from bending



Design of the conduction link design

3. Mechanical design and simulation verification

Al conduction link bolted to the Nb rings around the cavity

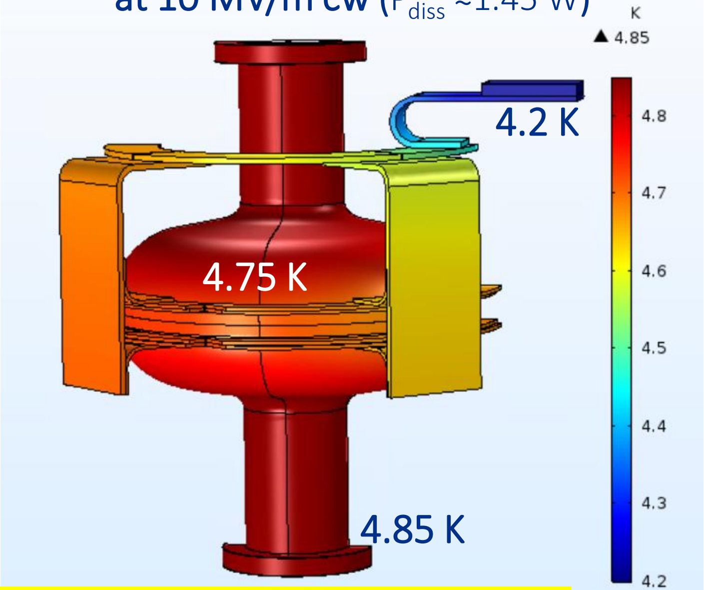


Nb_3Sn surface resistance (BCS from SRIMP + 10 nΩ)

RF + thermal simulations

Thermal conductivities, contact resistance, cryocooler capacity

Steady state temperature profile at 10 MV/m cw (P_{diss} ≈1.45 W)



Simulated conductance ($P_{diss}/\Delta T$) ≈ 2.6 W/K

J. Thompson and R.C. Dhuley, 2019. https://doi.org/10.2172/1546003

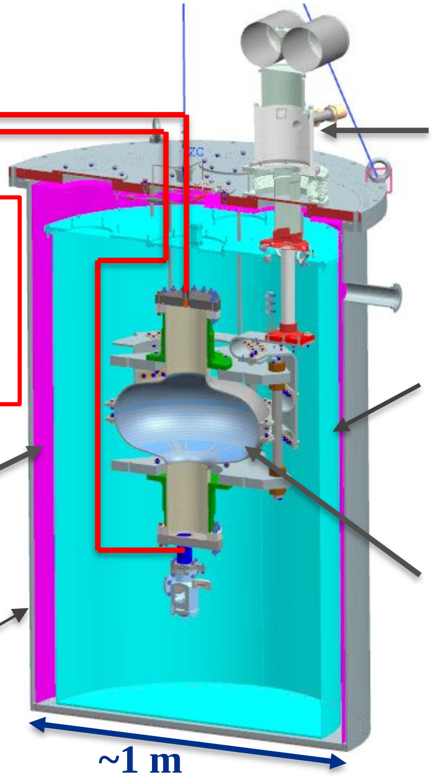
R.C. Dhuley *et al.*, ***IEEE Trans. Appl. Supercond.***, 2019. https://doi.org/10.1109/TASC.2019.2901252

Conduction-cooled SRF cavity measurement setup at Fermilab

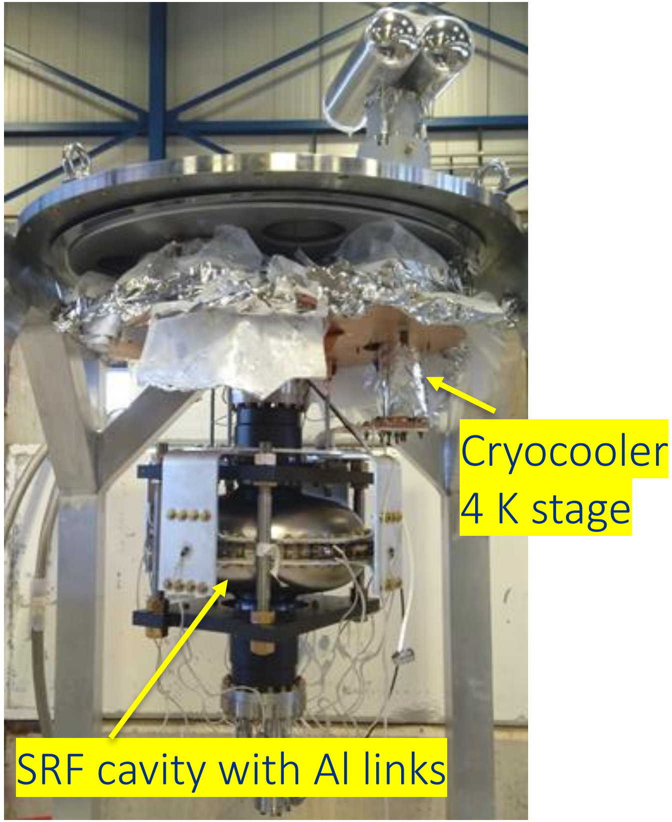
R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020 (to appear). https://www.osti.gov/biblio/1572517

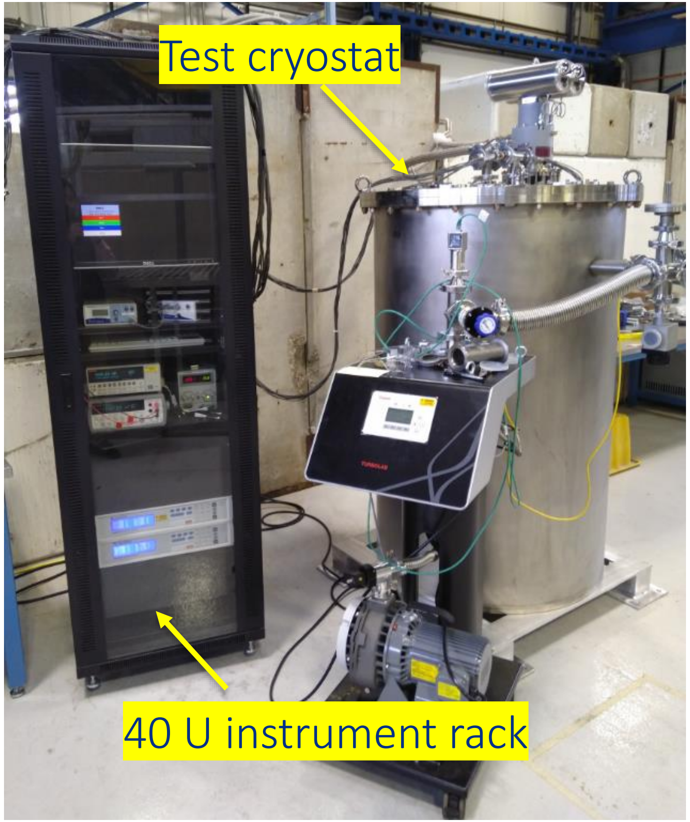
Euclid Techlabs

RF system
- 10 W cw @ 650 MHz, 1.3 GHz
- Resonance locking
- P_f, P_r, P_t, τ_L measurements



Conduction-cooled SRF cavity measurement setup at Fermilab





Cavity processing and test sequence

Niobium cavity with conduction rings

⇩ RF check, bulk EP, 800 ^{0}C bake, light EP, HPR

2 K VTS test of niobium cavity (check 10 MV/m cw)

⇩

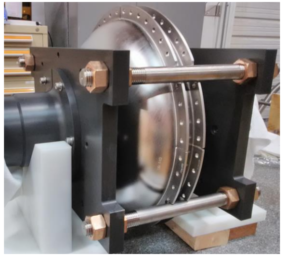
Coat with Nb_3Sn

⇩

4.4 K VTS test of Nb_3Sn cavity (baseline test)

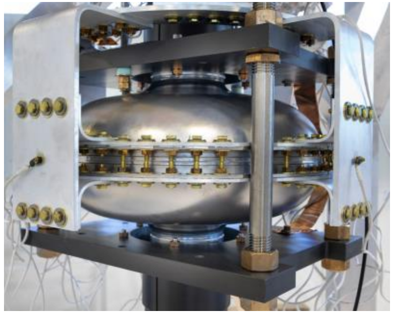
⇩ Warm-up, connect thermal link

Conduction-cooled tests of Nb_3Sn cavity



Cavity as received from vendor

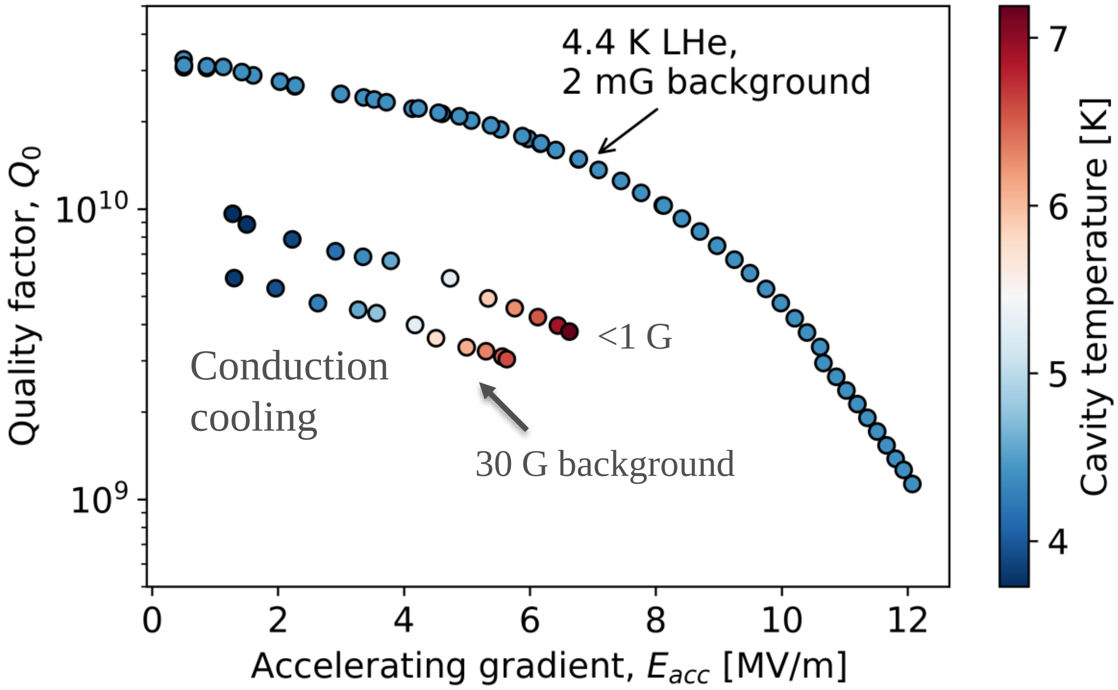
Cavity on HPR tool



Cavity dressed with Al link

First results of conduction-cooled Nb_3Sn cavity

R. Dhuley, S. Posen, M. Geelhoed, O. Prokofiev, J. Thangaraj, ***Supercond. Sci. Technol.***, 2020.
https://doi.org/10.1088/1361-6668/ab82f0



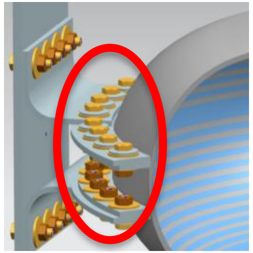
(max. E_{acc} limited by RF power)

Fermilab VTS baseline with 4.5 K LHe

- $Q_0 = 3\times10^{10}$ at E_{acc} = 1 MV/m
- max E_{acc} = 12 MV/m

Conduction cooling

- $Q_0 = 5\times10^9$ at E_{acc} = 1 MV/m
- max E_{acc} = 5.5 MV/m



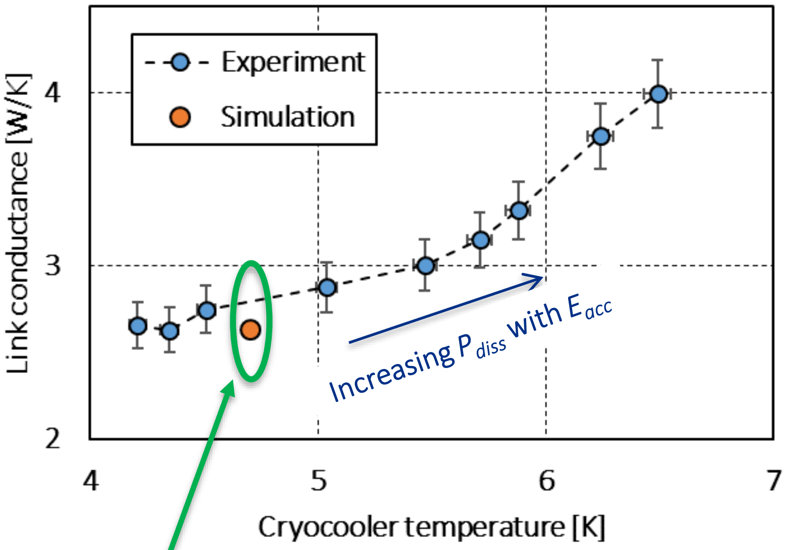
disc springs ~30 G led to large flux trapping

Conduction cooling with <1 G disc springs

- $Q_0 = 1\times10^{10}$ at E_{acc} = 1 MV/m
- max E_{acc} = 6.6 MV/m

Conduction link performance, cavity thermal stability

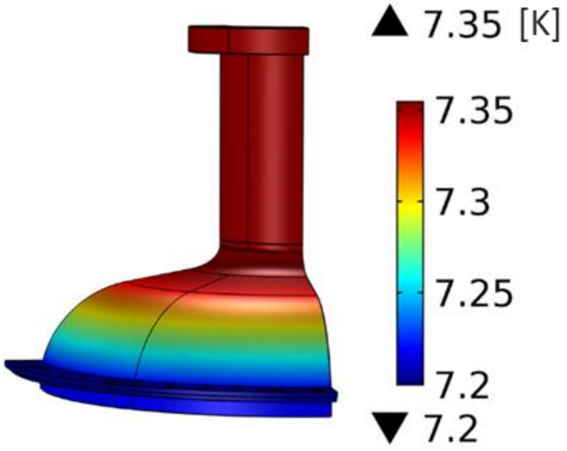
Comparison of measured and simulated link thermal conductance



Good match!

Computed cavity surface temperature at steady state with 6.6 MV/m cw

- Ring temperature = 7.2 K (boundary condition)
- RF dissipation = 4 W (boundary condition)



Courtesy : R. Kostin (Euclid Techlabs)

- $\Delta T_{spatial}$ <0.15 K
- T_{max} < 9 K

Ongoing research to achieve 10 MV/m

Improving magnetic hygiene to reduce trapped flux

Steel (magnetic)

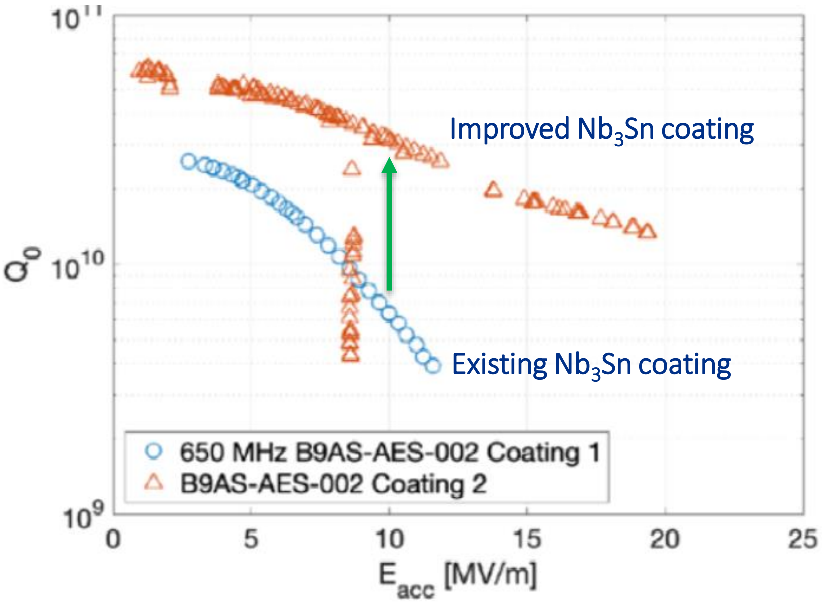
Beryllium copper (non-magnetic)

- Active compensation, additional shield

Flux expulsion by slow/fast cooldown

- Natural "slow" cooldown
- Turn OFF cryocooler -> warm up above 18 K
- Turn ON cryocooler for "fast" cooldown

Improving Nb_3Sn coating procedure



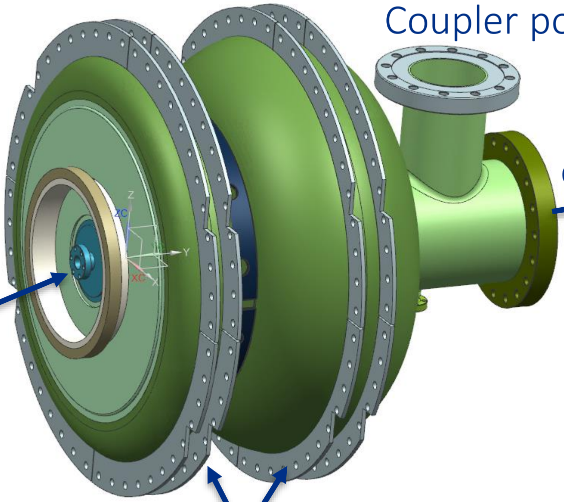
S. Posen *et al.*, https://accelconf.web.cern.ch/srf2019/papers/thfub1.pdf

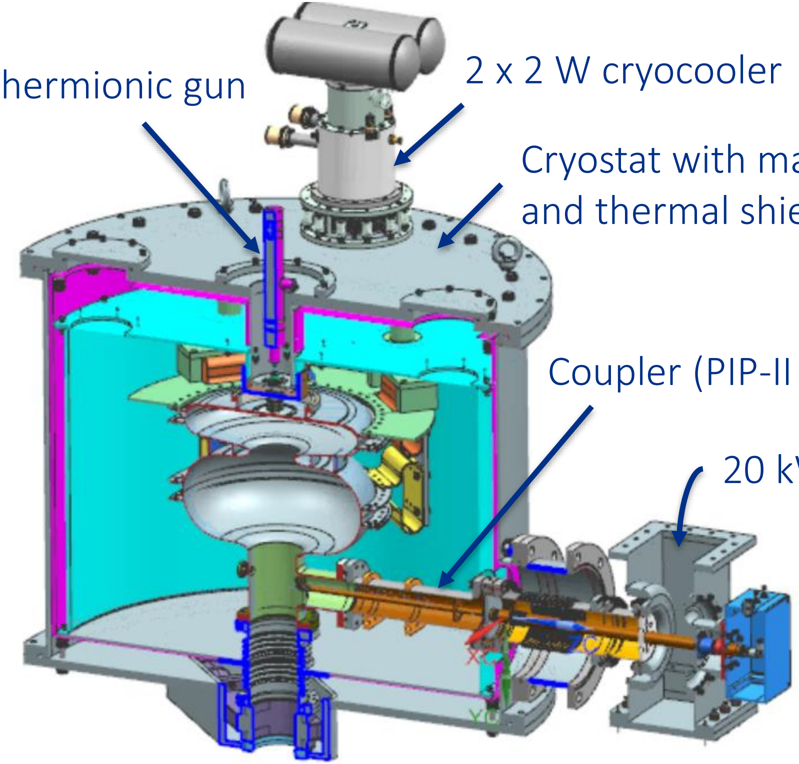
Conduction-cooled SRF accelerator program at Fermilab

- Prototype development: efficacy and performance demonstration
- Design studies for an industrial scale machine

Prototype electron accelerator development (1.6 MeV, 20 kW)

Supported by US Army Corps of Engineers (ERDC)





E_{acc} ≈4.7 MV/m; Cryo load ≈3.8 W @ 4.5 K

Design and economics studies of industrial scale SRF electron accelerators (10 MeV, >>100 kW)

Supported by DOE HEP Accelerator Stewardship Program

Phase (year) / Fermilab PI	Activity	Stewardship partner
I (2016-17) / R.D. Kephart	Conceptual design of a 250 kW and economic analysis of a 1 MW facility	MWRD of Greater Chicago
II (2017-18) / J.C.T. Thangaraj	Conceptual design of a 1 MW module and economic analysis of a 10 MW facility	MWRD of Greater Chicago
III (2019-in progress) / R.C. Dhuley	Practical cryogenic design and cost analysis of a 1 MW module	General Atomics

Design reports available at: https://iarc.fnal.gov/publications/

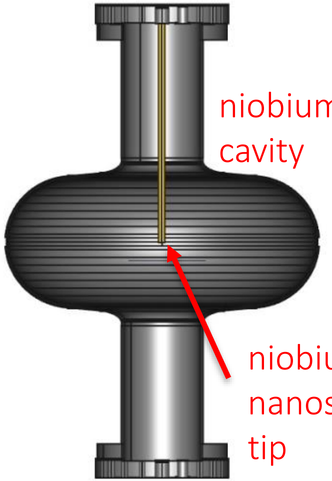
New research facilitated by Fermilab's conduction-cooled SRF cavity project

Development of SRF based field emission sources

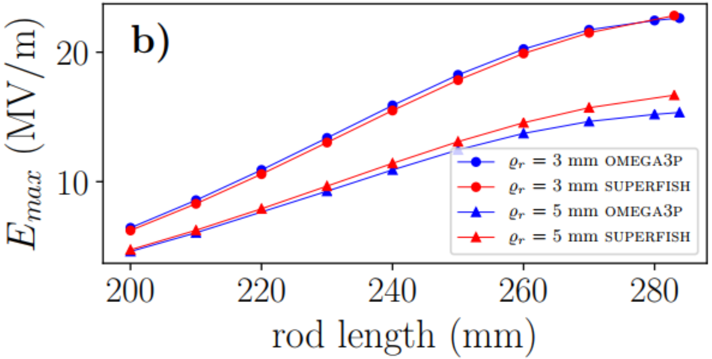
PI: Dr. Philippe Piot (NIU/ANL)

NIU-Fermilab collaboration

- field emission cathode with nanostructured surface located in high e-field region of an SRF cavity
- use cw operation to produce high repetition rate field emission (high I_{avg})



Cathode surface e-field
(650 MHz cavity, 1.6 W cryo-cooling)



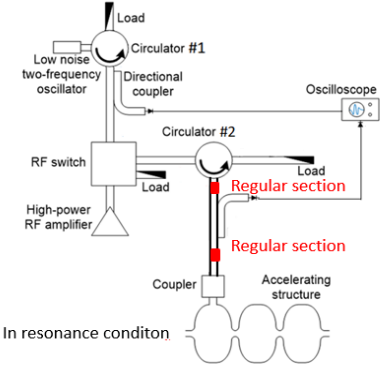
Mohsen *et al.*, http://accelconf.web.cern.ch/ipac2019/papers/tupts083.pdf

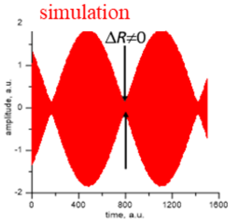
Method for "in situ" measurements of unloaded Q-factor of an SRF resonator installed in a cryomodule

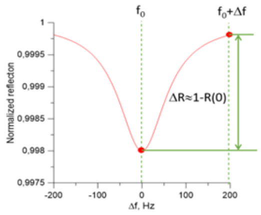
PI: Dr. Chunguang Jing (Euclid Beamlabs)

- In modern SRF cavities Q_0 can be as high as 10^{10}-10^{11} ($\beta \geq 10^3$) so that the reflection R is near to 1 in a whole frequency band, which makes it very challenging to monitor the Q factor during the operation.
- Funded through DOE SBIR program (SBIR Phase I Grant #DE-SC0019687), we proposed to use the dual frequency method to measure the Q_0 in its operation setup.

Proposed measurement configuration and simulation

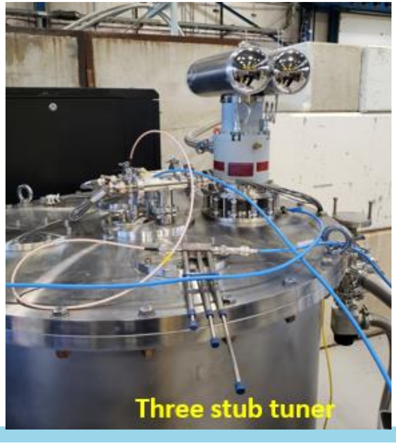


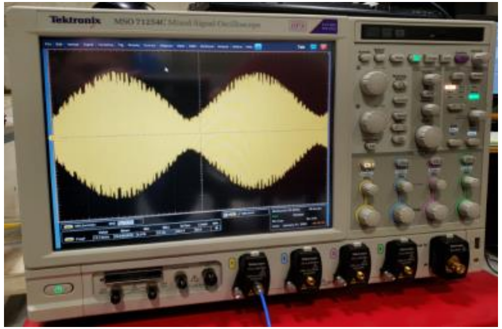




$$Q_0 = \frac{2Q_l}{R(\Delta f) - R(0) - 2\chi}$$ as $\chi = (R_{max} - R_{min})/2$.

The 1st Proof of Concept experiment in 2019 at Fermilab IARC (650 MHz SRF cavity with conduction cooling)





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Summary and outlook

Cryocooler conduction cooling offers simple, reliable cryogenics for developing industrial SRF e-beam accelerators

Conduction-cooled SRF R&D at Fermilab

- first demonstration >6.5 MV/m cw on a 650 MHz Nb_3Sn coated cavity
- prototype development and high power accelerators designs in progress

Cryocooler conduction cooling can greatly expand access to SRF

- university groups, industries can embark on in-house SRF R&D without needing full stack helium cryogenic systems

Acknowledgement

This presentation has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

- Conduction-cooled SRF demonstration: J.C.T. Thangaraj, Fermilab LDRD
- Nb_3Sn development: S. Posen Fermilab LDRD, S. Posen DOE Early Career Award
- Accelerator design studies: R.C. Dhuley HEP Accelerator Stewardship Award
- Compact SRF accelerator development: US Army Corps of Engineers (ERDC)

HEP Accelerator Stewardship

US Army Corps of Engineers (ERDC)

NORTHERN ILLINOIS UNIVERSITY
Northern Illinois Center for Accelerator and Detector Development